Fully embedded optical and electrical interconnections in flexible foils

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Abstract

This paper presents the development of a technology platform for the full integration of opto-electronic and electronic components, as well as optical interconnections in a flexible foil. A technology is developed to embed ultra thin (20 µm) VCSEL's and Photodiodes in layers of optical transparent material. These layers are sandwiched in between two Polyimide layers to get a flexible foil with a final stack thickness of 150 µm. Optical waveguides are structured by photolithography in the optical layers and pluggable mirror components couple the light from the embedded opto-electronics in and out of the waveguides. Besides optical links and optoelectronic components, electrical circuitry is also embedded by means of embedded copper tracks and thinned down Integrated Circuits (20 µm). Optical connection towards the outer world is realized by U-groove passive alignment coupling of optical fibers with the embedded waveguides.

Key words: Opto-electronic packaging, flexible, thin chip, VCSEL, optical interconnect, embedding

Introduction

Embedding of optical and electrical circuitry in flexible foils is not just an extension to rigid carrier systems, but it enables a whole range of new dedicated applications and adds cost, speed, weight and volume improvements to existing rigid applications. The complete stand-alone flexible package presented in this paper adds an increase in compactness and weight beyond the possibilities of rigid substrates.

The work presented can also be considered as the development of a generic research platform for flexible optical communication. Two clear trends in the world of electronics have been witnessed in the past 10 years. On one hand, optical communication is no longer serving only long distances but has also been introduced in the on-board communication for chip to chip data transfer [1-2]. On the other hand, flexible electronics have proven their worthiness in portable applications and their profit in cost reduction because of roll to roll production feasibility [3-4]. One can expect that both trends will meet each other in the near future.

Several research groups have developed a hybrid rigid / flexible optical link, consisting of a flexible waveguide connection between two rigid boards containing the electronics and the opto-electronics. What follows describes a fully flexible package of multimode waveguides and active opto-electronic devices.

Materials

The development of opto-electrical PCB's on rigid substrates is growing towards maturity, however their use in applications is still limited to some high-end purposes. The main target for optical PCB's are optical backplanes, demanding very low light propagation losses of the optical path. Bulk materials for these optical layers are chosen to have low losses at a typical wavelength of 850 nm for data communication and 1.3 or 1.55 µm for telecommunication applications. They must have the right processibility properties in view of UV-crosslinking ability, spin-coating, temperature- and chemical resistance and mechanical brittleness. Special care must be taken to ensure the compatibility of the production process with the standard PCB production processes. This means the materials should be inert to production solvents and temperatures used during the production steps of the electronic assembly afterwards. The substrate should be physically and chemically stable in temperatures of about 280 degrees during solder reflows and in temperature cycling's from -40 to +85 degrees.

Truemode Backplane^{TM} Polymer [5], Ormocer® [6], LightLink and Epocore [6] are materials which meet these requirements and have shown good results when applied on rigid substrates in the past. The existing optical materials are however not flexible and strong enough to be bended without cracking or damaging. Therefore these layers are sandwiched between two spin-coated Polyimide (PI) [8] layers, one at the top and one at the bottom, which absorb all stress and pressure during bending. This way the flexibility and durability of the substrate is significantly increased. The final mechanical reliability and robustness can however not be extended to the high demands of the flex market. Further material development is ongoing within the consortium of the FAOS Project (IWT funded Flemish project: Flexible Artificial

Optical Skin) and the Phosfos Project (EU FP7 Funded project: Photonic Skins for Optical Sensing) to create novel cross-linkable polymers with improved properties for the flexible applications. During the past 4 years a lot of flexible optical materials have been developed by global material providers also, but these materials are often commercially unavailable and under development.

Development of a flexible optical foil

A flexible optical foil is considered to be a flexible, bendable foil containing optical transparent layers with light confining tracks to route the light signals over the entire foil size. Here fore we fabricate a stack of a cladding-layer, a core-layer and another cladding-layer. Isolating tracks in the core-layer and consequently surrounding the track completely with cladding material, results in the creation of optical waveguides. This is a well proven principle for optical interconnections on rigid boards. Experiments have shown that the flexibility, strength and reliability of the completed layer-structure is significantly improved when the optical layers are sandwiched between two Polyimide layers as described in the “materials”-section. This approach of consecutive layer stacking, results in a symmetrical build-up. The symmetry of the final stack cannot be underestimated since it has a big impact on the warpage of the foil.

The processing of the optical foil is performed on a rigid temporary glass carrier to ensure the compatibility of the fabrication scheme with the standard PCB fabrication processes.

The proposed process layout results in a very light, thin (160 µm total thickness) foil with a high tensile strength due to that of Polyimide. High flexibility is achieved and the minimum mechanical bending radius before damaging the structure is set to 2.5 mm. Figure 1 shows a photograph and a cross-section of the optical foil.

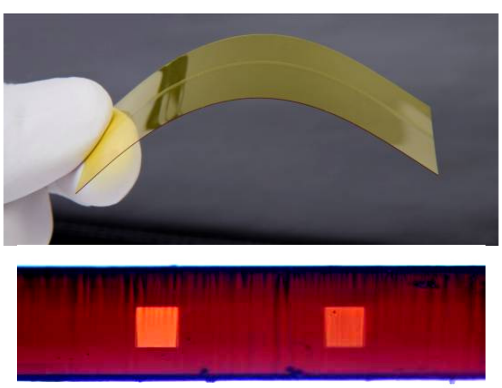

Figure 1: Photograph and cross-section of a flexible optical foil in Epocore material.

The foil has been realized and the adhesion matters have been optimized for the 4 optical materials discussed in the material section of this paper.

Thinning of opto-electronic components

Embedding rigid components like VCSEL’s and Photodiodes inside flexible substrate asks for special measures to ensure the flexibility. Standard commercially available optoelectronic components have a typical thickness of 150 µm. This means that the total substrate thickness will be larger than 150 µm. Since we have to apply Polyimide and waveguide layers on top of the embedded die, the total thickness will become way too large to ensure good flexibility of the substrate. To counter this problem, we developed a thinning process for the dies, to reach thicknesses smaller down to 20 µm. This way the dies have even proved to be bendable, which increases the reliability of the package.

The naked dies are mounted face down onto a temporary rigid glass carrier with a dedicated wax, together with large dummy GaAs chips to spread the applied pressure on the carrier (the VCSEL and Photodiode array chip are very small : 1000 x 250 µm) the applied load on the die is too high.

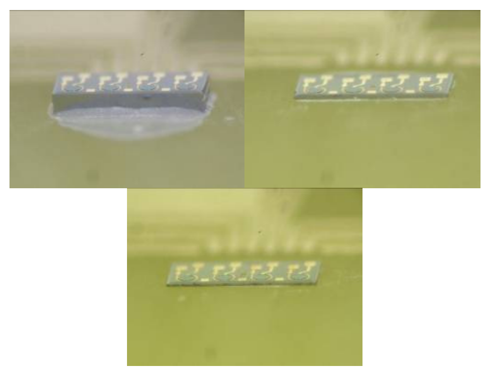

Figure 2: Tilted side view of a 150 µm thick photodiode 1*4 array (*top left*), a lapped PD array (35 µm) (*top right*) and a lapped + polished PD array (20 µm) (*bottom*).

Due to the thinning process, damage is done to the backside of the thinned die. Any initial microcracks can cause failure of the die when it is bended over a small bending radius. Therefore we need to achieve low roughness of the back side which imply that the initial cracks are very shallow and then negligible. This is the reason why the last 15 µm of the total thickness is removed by very slow, low damage polishing step. Figure 2 shows a photograph of a non-thinned, a lapped and a lapped + polished photodiode array. Figure 3 shows the roughness of the complete backside of a thinned VCSEL after the lapping step (top left) and after the polishing step (top right), measured with a non contact profilometer (WYKO). For a 350*1000 µm2 VCSEL, we see a difference in height of 3 µm between the lowest and highest point, which is a negligible height difference.

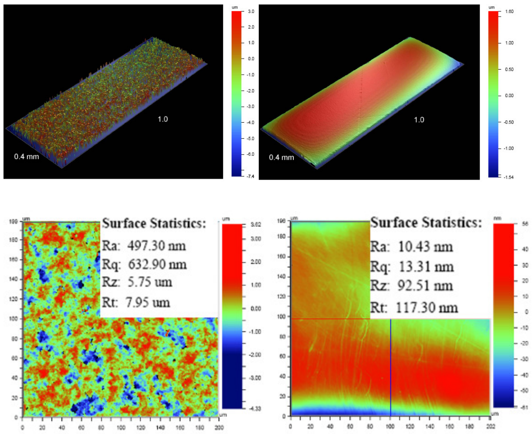

Figure 3: Profile of the backside of a lapped (*top left*) and a lapped + polished (*top right*) VCSEL array. Roughness measurement on a 50*50 µm x µm area for a lapped (*bottom left*) and a lapped + polished (*bottom right*) VCSEL array.

A roughness measurement for a rectangular area of 200*200 µm2 of a thinned VCSEL after the lapping step (left) and after the polishing step (right), measured with a non contact profilometer (WYKO) shows that the roughness of the lapping step is clearly reduced from 500 to 10 nm Ra by the polishing step (Figure 3 bottom).

The thinning process for opto-electronic components does not allow damage to be done to active layer of the die. However the thinning could induce stress inside the die and the active layers. To test the influence of this stress on the optical characteristics of the VCSEL, the VCSEL was attached to an FR-4 substrate and then wire bonding to metal tracks on the substrate. This was done for a non thinned VCSEL array (150 µm), a lapped VCSEL array (50 µm) and a lapped + polished VCSEL array (30 µm). Each array consists of 4 VCSEL's. The LI curves of the VCSEL's were measured and compared. Also the current threshold of each mode produced by the VCSEL are measured and compared. Averaging the results showed us that there is no noticeable change in these parameters due to the thinning of the components, so we can say that the thinning of opto-electrical components induces no change in optical behavior of the VCSEL.

Embedding of thin opto-electronics in the flexible foil

The flexible optical foil presented so far is a passive substrate which can only be used for guiding, splitting, multiplexing, etc. Many reports have been published in the past 2 years, demonstrating foils like presented here to link two rigid boards or connectors with a flexible optical link. This paper however shows "the next step to flexibility" by integrating the actives inside this foil. By thinning the actives, they are physically bendable. The connectorisation electrically and optically of these actives with each other, with the passive waveguides and with the outer world is discussed in this research.

The embedding of opto-electronic components in the optical foil has been realized so far for the Truemode Backplane Polymer^{TM} only. Figure 4 shows the schematic overview of the process flow used to embed thinned VCSEL and PD arrays in the cladding layer of the flexible optical foil.

For planarization reasons, the VCSEL's and Photodiodes are placed in a cavity inside the under cladding layer.

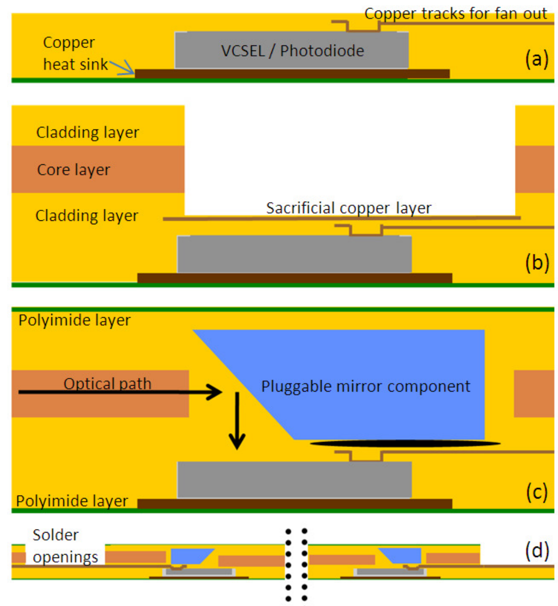

Figure 4: Schematic overview of the process flow for the production of an active flexible opto-electrical foil.

The cavities are laser ablated (KrF Excimer laser; 248 nm wavelength) because of the high-accuracy-needs for the dimensions of the cavity. The cavity must be obviously larger than the die, but cannot be too large because the cavity must perform passive alignment of the die. This way a 10µm positioning accuracy of the die can be obtained. Fine pitch die placers can even lower this accuracy to several microns. In between the under cladding layer and the PI layer, a metal island is deposited. This acts as a heat sink for the active components and also as a laser stop. This way we achieve good depth control of the cavity and fast processing.

The active components are mounted inside the cavity with a low temperature curable adhesive. The adhesive needs to be heat conductive but not electrical conductive and needs to show very low viscosity to fill the whole cavity with a thin adhesive film. To reach the high alignment requirements and coupling efficiencies, it is necessary that the die is perfectly leveled with the substrate surface and not tilted. In the next step the die is covered with a cladding layer of 10 µm to finish the embedding of the die. This layer has proven to be well planarised, meaning that the cavity principle works well. Laser ablated micro-via's are then made to the embedded contact pads and metalized. Metallization is needed to fan out the small pitch contact pads of the embedded VCSEL and Photodiode array's (250 µm pitch) towards larger pitch contact pads (2 mm pitch) on the substrate surface.

The production of waveguides on top of the embedded dies is done with standard lithography and an alignment error in relation to the active area of the optoelectrical components is smaller than 5 µm. 45 degrees coupling structures are fabricated externally in flexible Polyimide material and embedded in the flexible optical foil on top of the embedded opto-electronics.

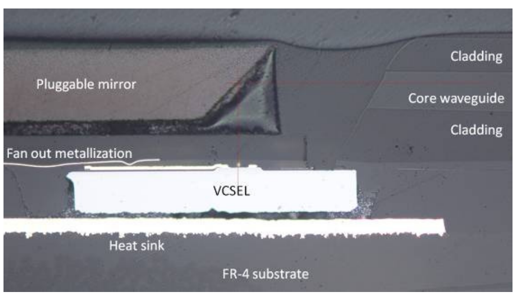

Figure 5: Cross-section of an embedded VCSEL array in the flexible optical foil.

The whole structure is then again covered with a cladding layer to cover the embedded component and to obtain final planarization. Figure 5 shows a cross-section of an embedded VCSEL array in Truemode Backplane Polymer^{TM} together with the coupling component and the galvanic interconnection. As a demonstrator, a 2 cm long optical link between a thinned VCSEL and Photodiode was embedded inside the optical foil, which shows a total optical loss of about 5 dB for the complete link.

Embedding of IC's in the flexible optical foil

To enhance the functionality and intelligence of the flexible optical foil, Integrated Circuits (IC's) can be embedded in the layer build-up in the same way as the opto-electronic components. The embedding of IC's causes no demand for extra processing steps and the mounting of electrical and opto-electrical active devices can be done in one process step.

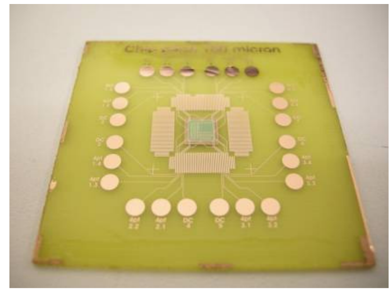

Figure 6: Photograph of an embedded thin (25 µm) IC in the flexible optical foil stack on an FR-4 substrate.

The thinning of IC's is done in a comparable way as the opto-electronic chips, but some inherent differences demand for some changes in process parameters and set-up. IC's are much larger in size and the base material is Si instead of GaAs for the opto-electronic devices, used in the previous described work.Because of the large size of the IC's, the dispensing of the glue underneath the chips must be well controlled. Figure 6 shows an embedded IC in the same layer build-up as the flexible optical foil, however the processing was done on an FR-4 substrate instead of a temporary glass carrier. 4 points measurements show a micro-via resistance lower than 20 mOhm.

Conclusions

The development of a series of new technologies is presented: Technologies needed to make the step from rigid opto-electronic boards towards completely flexible opto-electronic boards. First a flexible foil optical foil was realized with embedded optical waveguides, fabricated in commercially available optical transparent material, enhanced in durability by two mechanical supporting spin-on Polyimide layers. In a second phase, thinned (20 µm) VCSEL's and Photodiodes are embedded inside the under cladding layer of the waveguides. The embedded opto-electronics are electrically connected with the outer world using micro-via's, they are cooled down by the provision of heat sink features and they are optically coupled with the waveguide with embedded externally fabricated flexible coupling components. As a third phase, the functionality of the flexible opto-electronic board is enhanced by the embedded of drivers, amplifiers and intelligence IC's inside the same layer and in the same process as the opto-electronic components.

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